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James K. Newman
Iowa State University

Amy L. Kaleita
Iowa State University, kaleita@iastate.edu

2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

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Quantifying uncertainty of sediment TMDLs using a stochastic approach

James K. Newman, PhD Candidate

Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA
jknewman@iastate.edu

Amy L. Kaleita, Associate Professor

Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA
kaleita@iastate.edu

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Abstract. Scientific uncertainty inherent in the development of Total Maximum Daily Load (TMDL) standards for non-point source pollutants such as sediment hampers the program's effectiveness. Sediment is an important water quality parameter because deposition in streams and lakes adversely affects aquatic ecosystems. Equally important, suspended sediment is a transport mechanism for nutrients, pesticides and pathogens. This paper presents an alternative methodology that permits statistically valid calculation of sediment TMDL uncertainty. The sediment delivery computer simulation technology used for this project, the Geo-spatial interface for the Water Erosion Prediction Project (GeoWEPP), is capable of simulating single storm events and provides daily output useful for TMDL statistical analysis.

Keywords. Sediment, TMDL, Uncertainty analysis, GeoWEPP, Monte Carlo simulation

Introduction

The Total Maximum Daily Loads (TMDL) program was established as part of the Federal Water Pollution Control Act of 1972 with the goal of reducing water pollution to acceptable levels. Amended in 1977, this law became known as the Clean Water Act (CWA). As the federal agency responsible for administrating the program, the US Environmental Protection Agency (EPA) developed TMDL implementation rules and guidelines for state development of TMDL plans. A plan must be developed for each parameter (i.e. contaminant) determined to cause impairment of a designated water body. Sediment is one very important water quality parameter because deposition limits stream flow capacity, reduces water storage in lakes and reservoirs, and adversely affects aquatic ecosystems. Equally important, suspended sediment is a transport mechanism for nutrients, pesticides and pathogens.

EPA requires a margin of safety (MOS) for each target TMDL established. Most TMDL plans to date include only qualitative approaches (conservative assumptions) to comply with federal rules. In other words, uncertainty is not quantified through accepted statistical procedures. Improved uncertainty analysis and statistical techniques for TMDLs have been identified as science needs by the National Research Council (USEPA 2002). Following the Council report, some effort was made by the US scientific community to address the MOS issue but more work is needed.

TMDL rules were first developed at a time when point source pollutants were considered the primary cause of water quality degradation. TMDLs for point sources depend on low flow conditions and measurable point discharges. Today, non-point source pollutants contribute the greatest pollutant loads to water bodies. Science-based computer models have improved our understanding and ability to estimate no-point source loads. Determining TMDLs for non-point source pollutants is more complex because stream flow increases as pollutant loads increase. Therefore the TMDL may increase during storm event that cause higher runoff while the actual contaminant concentrations in the water may be below the MCL for the ecosystem.

The Total Maximum Daily Load (TMDL) development process for non-point sources is complex, with many decision points at which uncertainties exist (Figure 1). As a result, the MOS concept is interpreted differently from state to state, and even within states. Recently approved sediment TMDLs in Iowa use conservative input to the Revised Universal Soil Loss Equation (RUSLE) and the Modified Universal Soil Loss Equation (MUSLE) to assess the sediment source (IDNR 2007a, IDNR 2007b). However, MUSLE does not consider the probability of this storm event occurring during the time of the cropping year most susceptible to soil erosion. The probability of the 2 year-24 hour storm event occurring at any time in any given year is 50%. EPA suggests a MOS of no more than 10%.

The objective of this project is to develop methodology that will permit statistically valid calculation of sediment TMDL uncertainty. We propose the use of stochastically generated climate data from CLIGEN for Monte Carlo simulation input to the Water Erosion Prediction Project model (WEPP) as an alternative method for estimating sediment TMDLs (Total Maximum Daily Loads) in Iowa. The output generated by WEPP permits mathematical quantification of the variability of daily sediment yield predictions and a probability for achieving the TMDL target. The integration of GIS tools (GeoWEPP) adds spatial dimension for identifying areas of concern and treatment. In this paper we present an example application of the methodology using two different management scenarios within a 296 hectare watershed in Tama County, Iowa.

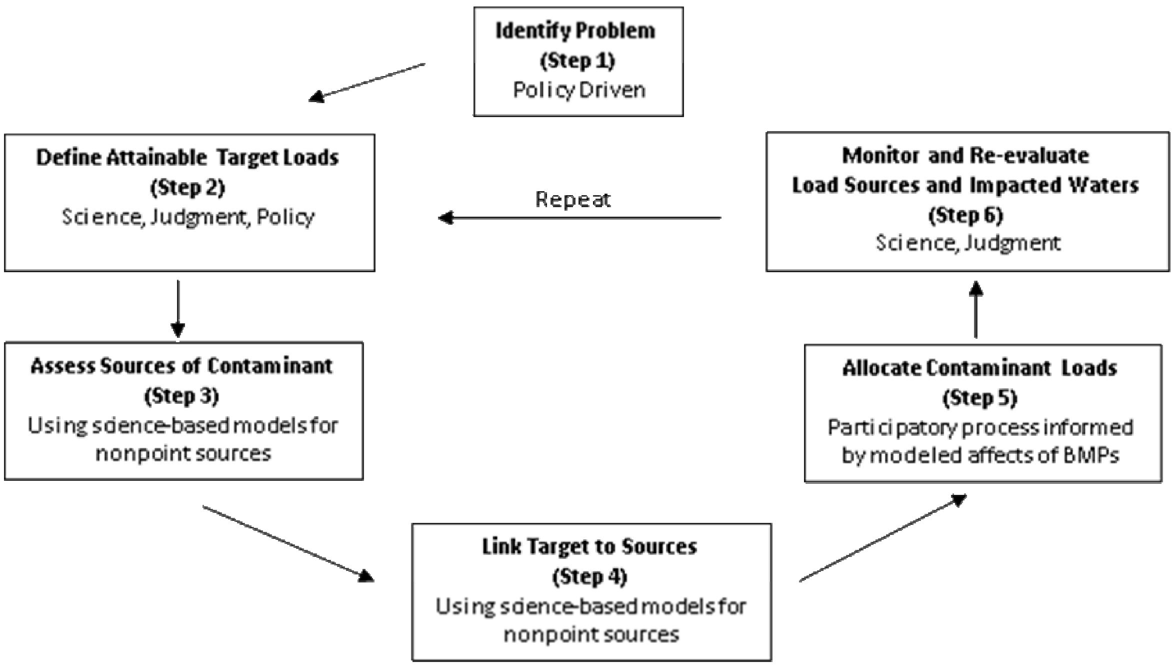

Figure 1 The TMDL process.

Methods

The methodology proposed here assumes that a target daily load for a stream segment has been determined. The assessment of the sediment source and quantification of its uncertainty is developed through the application of the Water Erosion Prediction Project model (WEPP). As an alternative to MUSLE for estimating sediment loads in Iowa watersheds, we proposed the use of stochastically generated climate data from CLIGEN as input into WEPP for Monte Carlo simulation. The daily output generated by WEPP permits mathematical quantification of the variability of sediment yield predictions and a probability for achieving the TMDL target. The integration of GIS tools through the GeoWEPP interface adds a spatial dimension for identifying areas of concern and treatment.

The model parameter input was obtained from the best available digitized data. Permanent land feature data for the study watershed is maintained constant while the stochastically generated climate parameters vary with each simulation. The accepted stochastic climate generator CLIGEN was used. Climatic parameter distribution data needed for CLIGEN are readily available for many regions of the globe. For this project, five thousand random climate sets of 20-years were generated from climatic parameter distributions of the Grundy Center station near to the example 296 ha watershed in Tama County, Iowa.

Climate was chosen as the variable input for the Monte Carlo simulation because sediment delivery is most sensitive to attributes of the storm event, particularly rainfall depth (Nearing et al. 1990, Tiscareno-Lopez 1993). Precipitation is the single most important source of uncertainty contributing to physical simulation model output variance (Zhang et al. 2004).

Two land management scenarios evaluated for demonstration are corn-soybean rotations under universal no-till and chisel plow. Several assumptions were required for this analysis. First, the daily precipitation event is assumed to occur uniformly over the watershed and individual storm events should affect sediment delivery independently. WEPP does not estimate stream bank erosion which is assumed not to contribute significantly to the sediment delivery. These assumptions limit the application of the WEPP model to a spatial scale to a fraction of the total area typical of TMDL watersheds in Iowa. Therefore, compliance by sub-watersheds is assumed to translate into compliance of the entire TMDL watershed. The target TMDL must first be defined by policy and/or science in order to determine the frequency of exceedance.

A 296 ha watershed in Tama County, Iowa, was selected for development of the methodology (Figure 2). Two universally applied management scenarios (chisel plow and no-till) were evaluated.

Important assumptions are that precipitation is the dominant source of sediment delivery event prediction variability, past measurements of daily precipitation adequately represent future daily rainfall event probability, individual storm events affect sediment delivery independently, the daily precipitation event occurs uniformly over the watershed, and stream bank and classical gully erosion do not contribute significantly to the sediment delivery.

For the example watershed presented here, we assume the target TMDL has been defined as 100 metric tonnes per day not to be exceeded more than once per year on average. Figure 3 shows the sediment yield output for each precipitation event during one example 20-year period stochastically generated by CLIGEN. The frequency of exceeding the TMDL target is determined for each of 5000 stochastically generated climate sets. The flowchart in Figure 4 helps describe the process. From the output of each of the 5000 simulations, the Monte Carlo simulation is constructed.

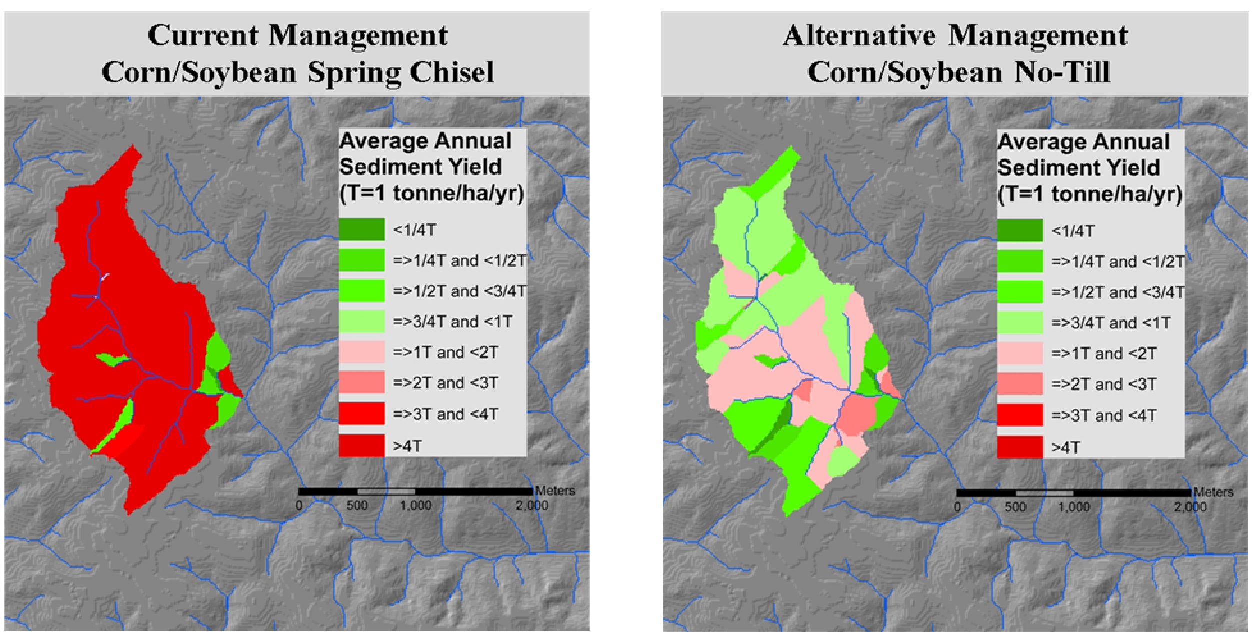

Figure 2. Mapped average annual sediment yields for one simulation of contrasting scenarios (296 ha watershed in Tama County, Iowa).

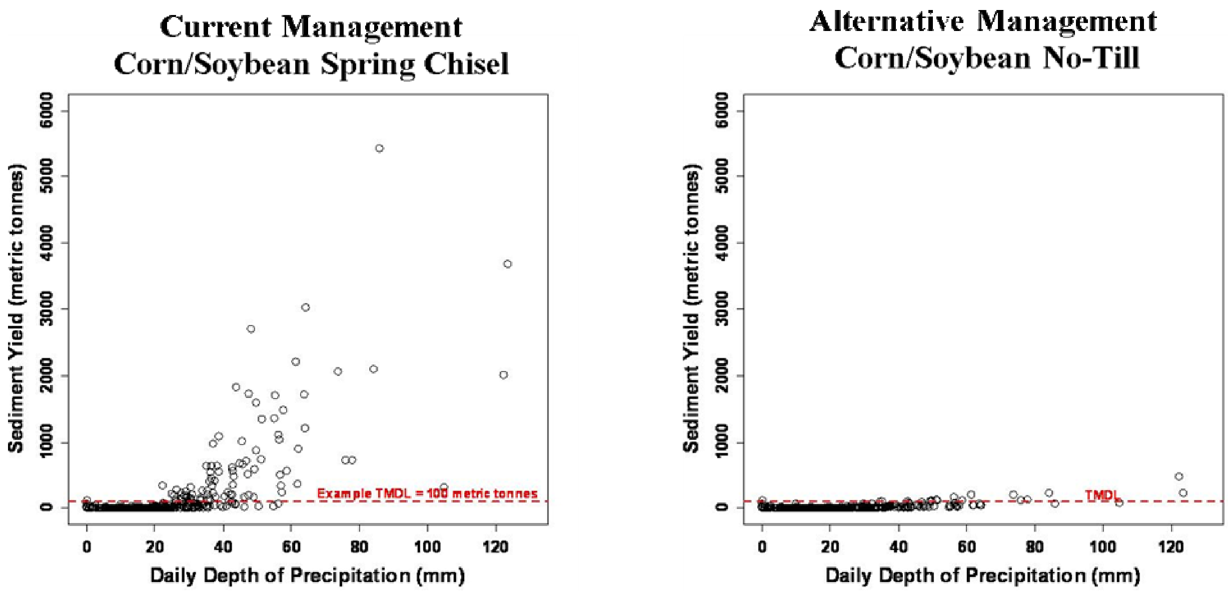

Figure 3. Total daily sediment yield events plotted as a function of precipitation for the respective scenarios mapped above showing the contrasting frequency of an extreme sediment delivery event (i.e. sediment yield greater than TMDL of 100 metric tonnes).

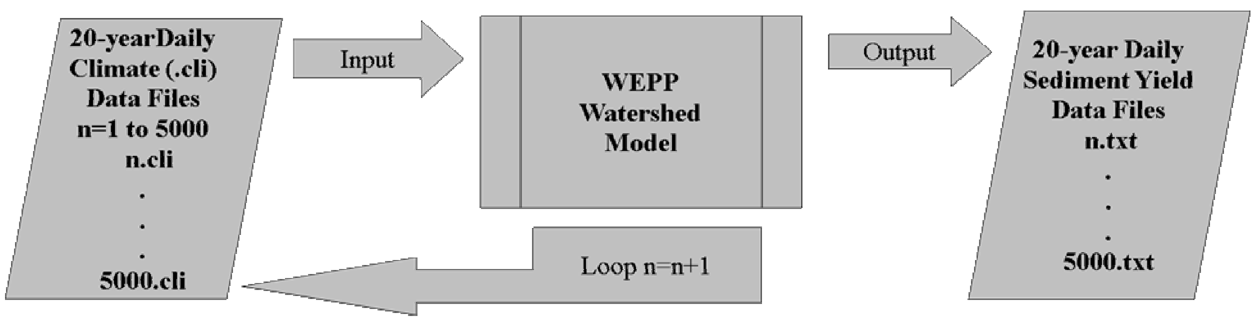

Figure 4. Flowchart of predicted sediment yield data generation.

Results and Discussion

Probabilities are determined from the Monte Carlo distributions as follows:

1. Count the number of events exceeding the TMDL of 100 tonnes in a 20-year simulation.
2. Repeat this count of TMDL exceedance events for each of 5000 simulations to create a list of 5000 integers for each scenario.
3. Build the frequency distribution histogram from the 5000 integers (Figure 5). For the no-till scenario, the exceedance event count ranges from 4 to 36 with a mode of 14. For Spring Chisel, the range is 50 (57-107) with a mode of 83.
4. Calculate the probability of exceeding the target for the scenario of interest from the Monte Carlo distribution.

Application of the methodology to the sample watershed described in this paper results in the Monte Carlo distribution presented in Figure 5. Assuming a goal of exceeding the target sediment load no more the once per year on average, the probability of achieving this goal is 89.56% under the no-till scenario, while probability under the chisel plow scenario is essentially zero. The example watershed of 296 ha (~1.4 square miles) used for development of this procedure required excessive computation time to complete 5,000 simulations. However, adequate statistical rigor may be achieved with less iteration. The mean and standard deviation of the Monte Carlo distribution stabilize after about 500 simulations in our example (Figure 6). Still, the analysis of multiple management scenarios in a timeframe conducive to stakeholder decision-making would require additional computational efficiency improvements.

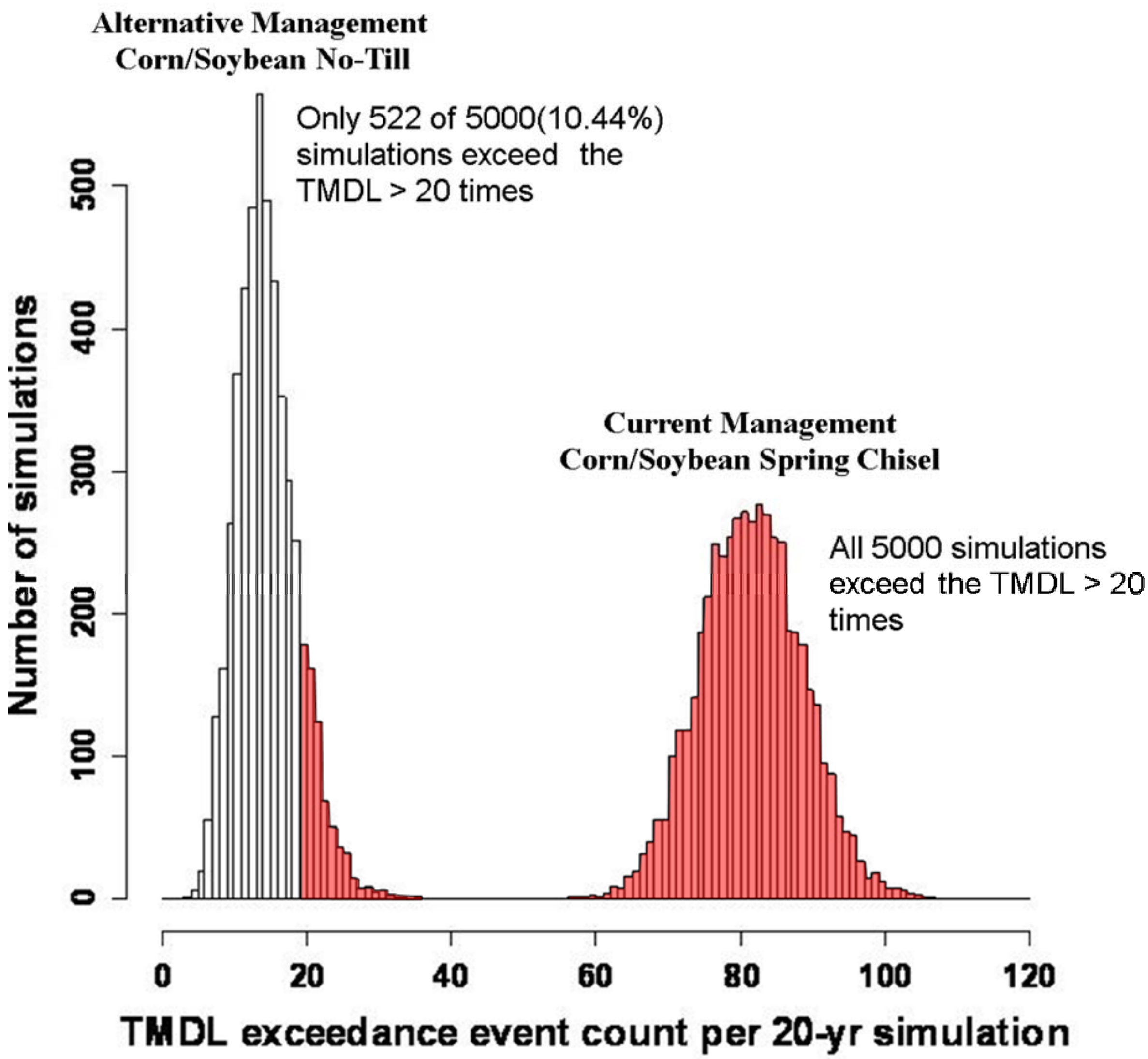

Figure 5 . Histograms of the Monte Carlo distributions for each scenario. Note: The non-exceedance probability for the alternative no-till scenario is 100%-10.44% = 89.56%.

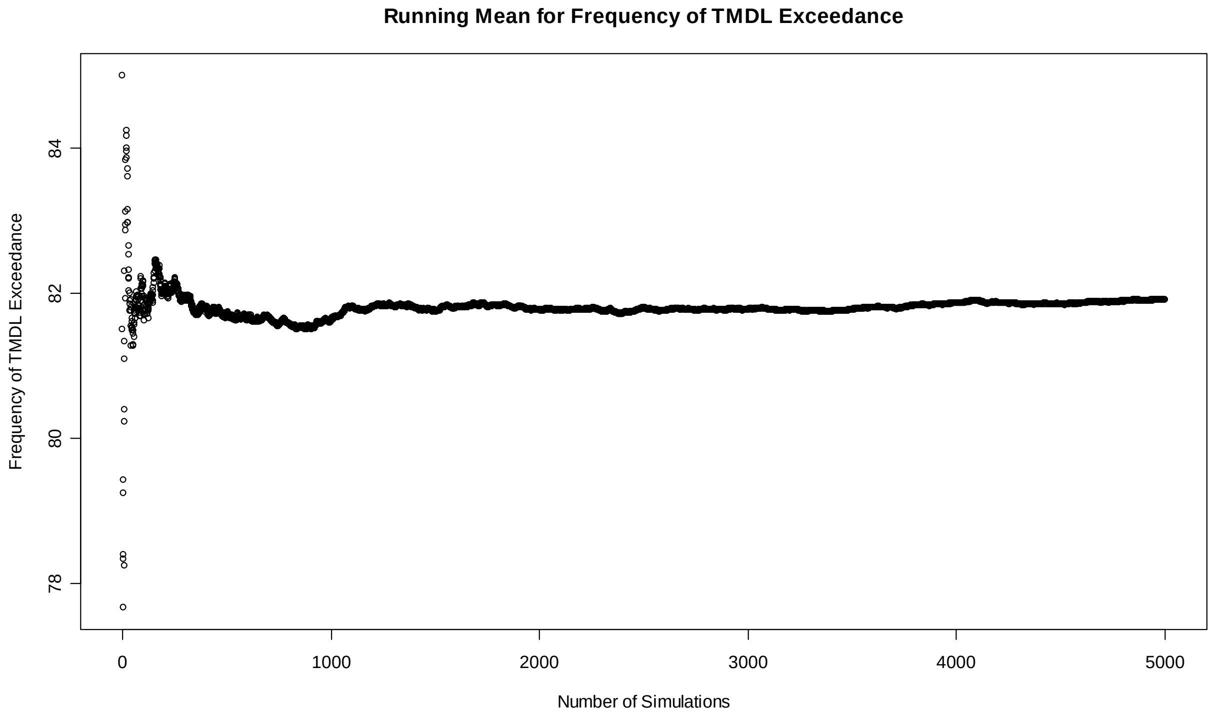

Figure 6a Mean of the Monte Carlo distribution plotted as a function of the total number of simulations performed.

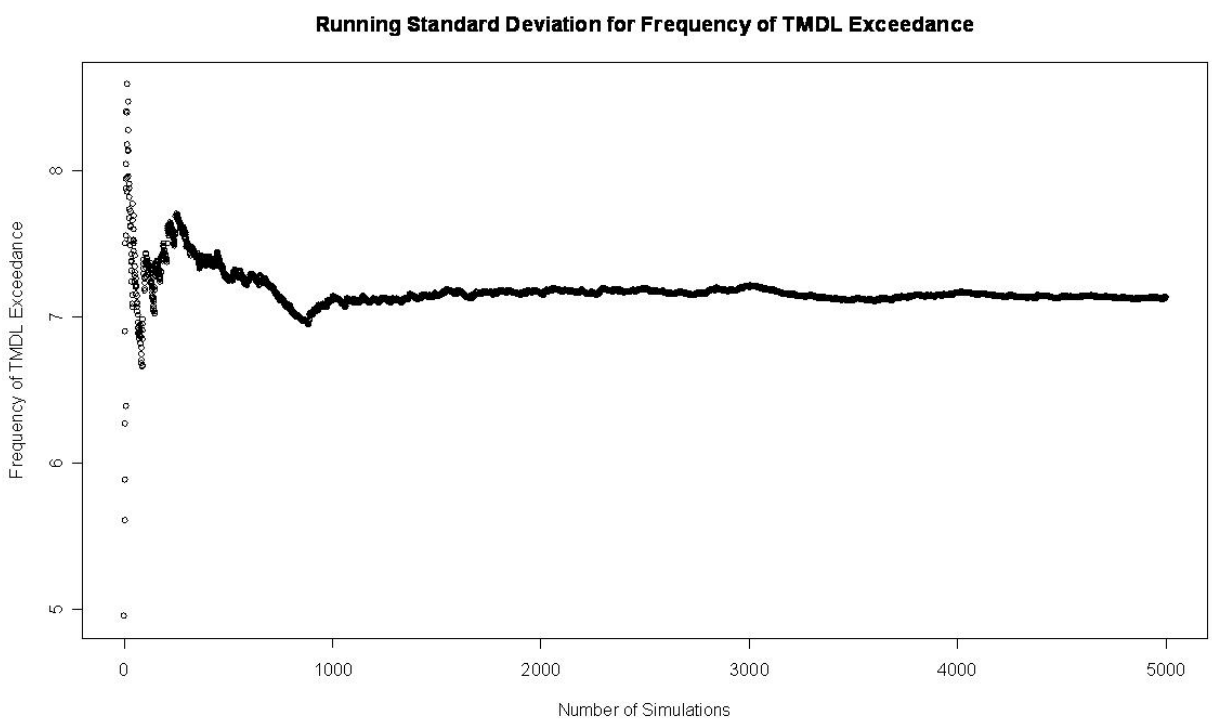

Figure 6b Standard deviation of the onte Carlo distribution plotted as a function of the total number of simulations performed.

Conclusions

The probability of exceeding the target sediment load for the sample 296 ha watershed can be explicitly quantified using the methodology presented in this paper. A corn-soybean rotation under applied chisel plow management was compared to a no-till scenario. Each scenario was universally applied to all agricultural lands within the watershed. The target TMDL was exceeded more than once per year on average in all 5000 chisel plow scenario simulations. By contrast, only 10.44% of the no-till scenario simulations exceeded the target TMDL more than once per year on average.

This methodology provides a measure of certainty for achieving the TMDL target and is easily duplicated for multiple land management scenarios. GeoWEPP is useful for indentifying sources of most significant sediment contribution and facilitates the targeting of management practices to areas of greatest concern. The code written for generation of the climate input and sediment delivery output can easily be modified for other watershed locations and land management scenarios. Computational efficiency, however, is an obstacle for Monte Carlo simulations using GeoWEPP, especially on larger watersheds. Adequate statistical rigor may be achieved with less iteration. The mean and standard deviation of the statistic of interest (i.e. the number of daily sediment delivery events exceeding the TMDL of 100 tonnes/day more than 20 times in 20 years) stabilize after less than 500 simulations.

Knowledge of uncertainty (spatially and temporally) is important for stakeholders to make informed decisions regarding sediment load mitigation that will be perceived as sensible and fair. GeoWEPP is particularly useful for identifying specific locations of high sediment yield. This information helps us better understand the soil erosion risk associated with these contrasting management scenarios and may be useful during the decision-making process and negotiating allocation of sediment loads.

Acknowledgements

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